Progress, Challenges and Perspective on Metasurfaces for Ambient Radio Frequency Energy Harvesting

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Abstract – In this paper, wireless power transfer (WPT) and energy harvesting (EH) technologies are reviewed in detail and the application of metamaterials and metasurfaces for WPT and EH is discussed. Specifically, we focus on the metasurfaces for ambient radio frequency energy harvesting (AEH) in the recent advances, comments, existing challenges and future directions. The performance of the metasurface- and antenna-based AEH systems is compared. The metasurfaces not only enable the efficient operation of the AEH system, but also extend the potential function for various kinds of energy harvesting devices, which is the influential progress of ambient electromagnetic energy harvesting.

Human's demand for energy is never-ending. Wireless power transfer (WPT) technology realizes the power transmission without wires,[1] which is theoretically more flexible and sustainable than traditional physical connections. The concept of WPT dates back to the Tesla's dream in the last century, although his experiment was a failure due to the lack of radio frequency (RF) technologies at that point.[2,3] With the iterative update of wireless communication and wireless sensing, WPT technology has ushered in its development from theoretical verification to commercialization during past decades.[4]

TABLE I. Comparison of various ambient electromagnetic energy sources.

Energy Sources	Wavelength Range	Power Density	Available Condition
Solar[9,13]	0.15 μm-4.0 μm	5-100 mw/m^2 (outside) 0.1-1 mw/m^2 (inside)	• During illumination time • Non-continuous available • Weather, time, location related
Infrared thermal radiation[10-12]	8 μm-13 μm	0.27 mw/m^2	• Need temperature difference • Continuous in day and night • Weather and atmosphere related
RF/Microwave[5-9]	0.1 mm-3000 m	2 μw/m^2-10 mw/m^2	• All-weather • All-day • Wide-spectrum range • Continuous and widely available

Nowadays, the development of artificial intelligence (AI) and 5G makes the internet of things becoming the future trend. A mass of low-power, miniaturized, intelligent mobile terminal devices and wireless sensor network (WSN) nodes are distributed in large-scale around the world.[5,6] It is a crucial issue that these wireless devices could work in a variety of complex environments adaptively and sustainably. Compared to the current battery powers with a limited life span, ambient energy harvesting technology can provide a continuous power supply solution for the low-power devices, enabling targets to capture energy actively or passively from the ambient to power themselves without replacing the battery.[7-9] There are many kinds of energy that can be collected in the environment, such as solar energy, thermal energy, kinetic energy, wireless RF/microwave energy, etc. The availability of these energy in real environments depends on such as the weather, time, location, and so on. Actually, the tremendous advances in wireless technology have given RF/microwave electromagnetic (EM) energy the potential to overcome these shortcomings. Essentially, according to the frequency spectrum allocation, the EM energy available in the environment has a very wide spectrum range including RF/microwave[5-9], infrared thermal radiation[10-12], solar[9,13], etc. Now, solar energy has been well utilized in industrial and commercial environments, but it has significant challenges such as low conversion efficiency (e.g. up to 23%) and limited to day time and good weather only. Infrared thermal radiation energy harvesting is able to collect heat flow from the Earth to the cold outer space, this part of the energy radiated to outer space is approximately equal to that of the incoming solar radiation on the Earth. It has great potential for renewable energy applications, but now it is studied only theoretically with very limited practical demonstrations[14]. In the early 1990s, the concept of RF energy harvesting was proposed to capture power from the ambient signal. The power spectrum of signals in the environment was mainly distributed in the wireless communication bands such as TV, GSM, LTE, Wi-Fi, etc. with a typically power density of 2 μw/m^2-10 mw/m^2 until now.[5,6,8] The three main available EM energy sources are compared and summarized in Table I. It is found that although the RF power source has the lowest power density, it also exhibits the broadest availability compared with the solar and infrared thermal energies if taking the time, weather and location into consideration. As the internet of things (IOT) and smart city evolve, the RF energy in the ambient is moving towards all-weather, all-day and wide-spectrum range with coexisting state, making microwave or RF energy ubiquitous, and low-power devices can continuously harvesting energy around them via radio waves continuously. That is, ambient RF energy harvesting is an inevitable trend in the low-power development of WPT system.[1,6] Its current main applications are as the primary or auxiliary source of power supply for low-power consumer electronics, medical implant devices, IOT sensor nodes and so on. Therefore, this paper mainly focuses on the ambient RF energy harvesting technologies. Figure 1 shows a brief summary of WPT and AEH.

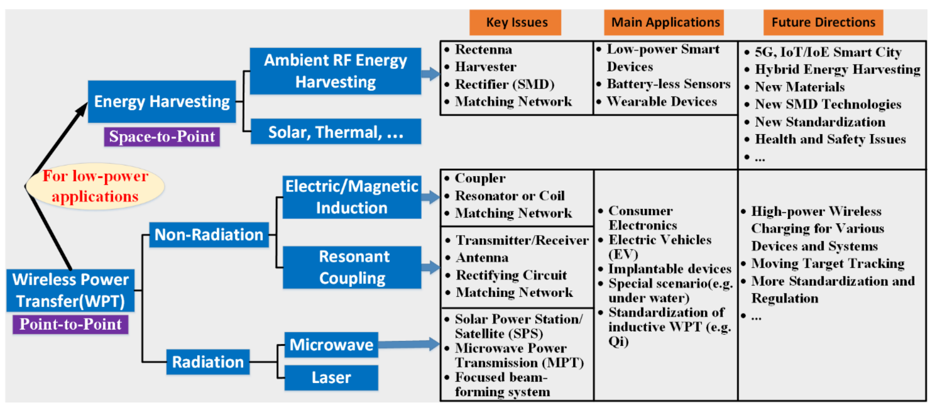

FIG. 1. The category, characteristics, key issues, main applications and future directions of WPT and AEH.

The WPT and AEH were commonly applied in different ways. WPT is mainly for point-to-point directional power transmission, and the power range is basically above W-level. It needs to systematically consider the transmitting part, the transmission medium and the receiving part. It is normally narrowband and high power. However, AEH is typically broadband and low power. It focuses on space-to-point energy capture, especially in the receiving part, with the power range from mw to μw or below. Among them, the rectenna is one of the most critical devices of the receiver for the WPT and AEH research. At present, the rectenna is widely used in many WPT or AEH applications, such as large-scale array rectenna for long-distance and high-power applications,[15,16] broadband or multi-band self-adaptive (e.g. frequency, power) rectenna for lower-power applications.[17-25]

On the other hand, metamaterials (MM) have attracted a lot of attention in many fields.[26] Metasurface (MS), as the most important MM, is a planar two-dimensional or quasi-two-dimensional metamaterial structure composed of sub-wavelength cells aligned periodically, whose complete concept was established in 2011.[27] The MS has widespread applications from microwave to optical bands due to its excellent performance and simple structure. Up until now, MS/MM has been applied for near-field WPT system, such as resonant coupling system,[28,29] medical implantable device,[30,31] near-field focused transmitter.[32,33] As a result, the near-field characteristics of transmission is enhanced by MS to improve the performance of WPT system mainly in efficiency and distance.[34,35]

MS for AEH applications to enhance its performance has been reported in the recent literatures, which is mainly divided into two research directions. One is to introduce the idea of MS in the receiving rectenna or add MS structure to improve antenna performance,[36-38] the other is a potential concept which is to use MS directly instead of the receiving antenna as an energy harvester. This concept is inspired by the so-called perfect EM absorber which was proposed in 2008.[39] For the energy harvester, the goal is to maximize the captured RF wave and then channel to the rectifying circuit, completing the conversion of the space RF energy to the available circuit power, rather than dissipating energy into the structure like the absorber.

The metamaterial particles were demonstrated for energy harvesting in 2012.[40] It is a planar single-layer finite array harvester consisting of 9×9 subwavelength split-ring resonator (SRR) cell structures operating at 5.8 GHz, and the resistive load located at the gap of each unit cell to store the RF energy by the SRR at its strong resonant frequency. Here, the MS replaced the conventional antenna as the energy harvester, and the efficiency of energy harvesting was redefined as the ratio of the available power received by the output terminal of the harvester to the incident power on the physical area of the harvester, which is different from the radiation efficiency of the antenna. The MS array harvester has higher energy collection efficiency than antenna at the same physical aperture due to the strong resonance and coupling between the unit cells which enhance its constitutive parameters and filtering characteristics. Therefore, the independent MM particles and the MS array harvester are essentially different, and the latter is fully developed to control the EM wave to match the free-space and load impedance to enhance the performance of AEH, which is also the development trend of current MS harvester. The planar SRR structure increases the transmission loss without a ground plane, thus the harvesting efficiency is less than 80% and is related to the incident angle. Related work has also been extended to the optical band.[41] It was reported that SRR cell with the transmission line also meets the challenge of harvesting efficiency.[42] Then, the improved SRR planar array composed of subwavelength electric-inductive-capacitive (ELC) cell is proposed as an energy harvester in 2015.[43] Unlike the SRR, the ELC cell with the additional via that connects the top and bottom grounded layers was employed to channel resonant surface currents into the load between via and ground, which was similar to the coaxial patch antenna. The ELC harvester, with maximum harvesting efficiency of 97%, has the comparable performance to the perfect

EM absorber. Consequently, the following energy harvester developed later is mainly improved according to this basic structure. Then, an 11×11 ground backed complementary split-ring (G-CSRR) array harvester was proposed as an improvement on the G-CSRR single element collector with high-efficiency and wide bandwidth compared to the 5×5 microstrip antenna array using the same physical area and operating frequency.[44,45]

To further improve the bandwidth of the MS energy harvester, a wideband G-CSRR array (each cell of the array contains 4 harvesting ports) was designed with four times more bandwidth than that of the G-CSRR at 5.5 GHz according to HPBW (Half Power Bandwidth) standard.[46] Another MS array with ring structure was reported to support broadband harvesting over the operating band from 6.2 to 21.4 GHz.[47] For the ambient RF energy harvesting, broadband or multi-band harvesters could collect and accumulate more energy in a wider frequency range than that from a narrow-band harvester, but the current proposed HPBW bandwidth standard may reduce the performance of wideband MS collectors. An effective solution is to improve the bandwidth standard of the MS collector by referring to the common bandwidth standard of the antenna and EM absorber.

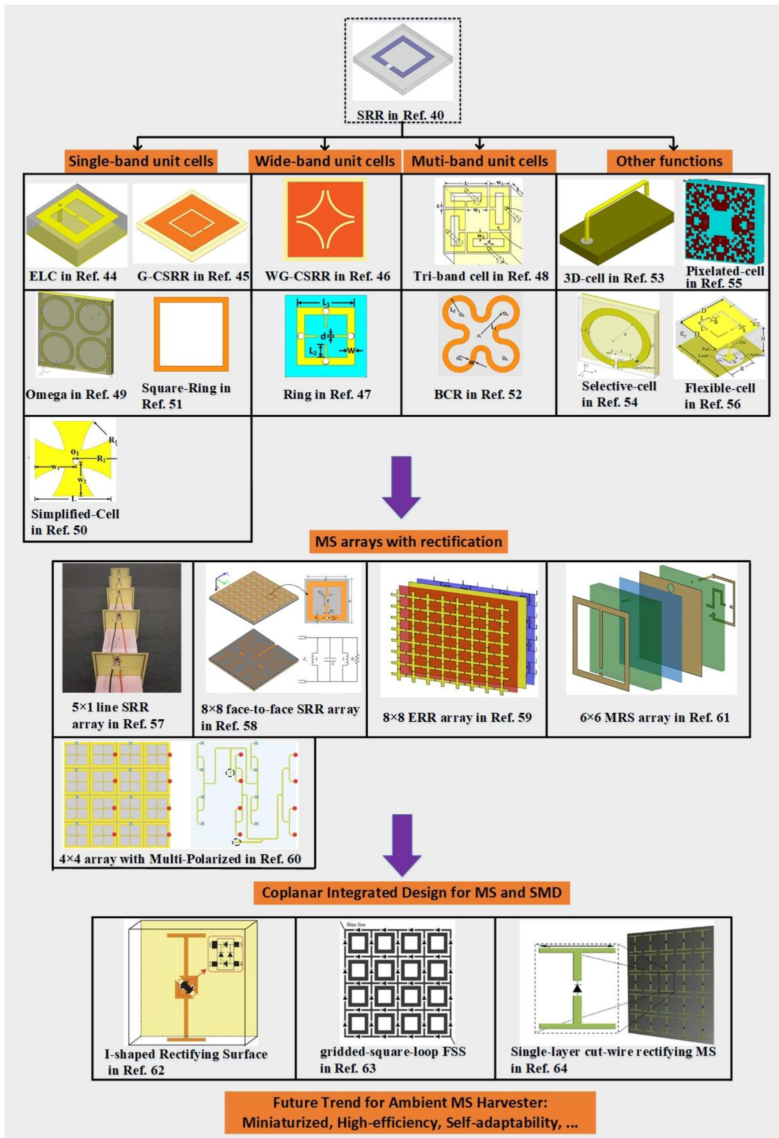

FIG. 2. Significant progress, evolution and future trend of the MS harvester for AEH. Reproduced from O. M. Ramahi, T. S. Almoneef, M. Alshareef and M. S. Boybay, Appl. Phys. Lett. 101, 173903(2012), with the permission of AIP Publishing.[40] Reproduced from T. S. Almoneef and O. M. Ramahi, Appl. Phys. Lett. 106, 153902(2015), with the permission of AIP Publishing.[43] Reproduced from B. Alavikia, T. S. Almoneef, and O. M. Ramahi, Appl. Phys. Lett. 107, 033902(2015), with the permission of AIP Publishing.[45] Reproduced from B. Alavikia, T. S. Almoneef, and O. M. Ramahi, Appl. Phys. Lett. 107,

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To maximize the reception of EM waves from unknown directions and random locations, there are also some noteworthy issues for the receiver with insensitivity of polarization and incident angle. At present, the compact rotating central symmetry SRR structure made the collector polarization-independent and wide-angle in the triple-band.[48] Another MS design with 'omega' pattern also realized the multi-polarization energy harvesting.[49] These two structures were similar to broadband collectors that each cell was designed with four harvesting ports, which significantly improves the performance of the collector but also brings the challenges to the overall complexity of the array harvester. Following that, the compact single-band collectors with a simple structure were proposed to achieve effective AEH and reduce collection port in each cell of MS.[50,51] Recently, a sub-wavelength multi-mode butterfly-shaped closed-ring MS has been proposed to be more suitable for high-efficiency AEH at three operating bands in reality.[52] The proposed MS was simple and miniaturized, and realized polarization-insensitive and wide-angle characteristics, but it still had a high impedance problem (e.g. difficulty in impedance matching) at the harvesting ports.

Some interesting features have also been introduced to the MS collector design. A 3D all-metal SRR was demonstrated to reduce the dielectric loss and improve the efficiency and bandwidth.[53] The SRR with capacitor loading could be selected to receive the left- or right-handed polarization of the incident wave.[54] The coded closed ring MS design could make the collector design fully automated to achieve high harvesting efficiency and improve the impedance matching of harvesting ports.[55] The use of flexible materials for MS could enhance the conformal capabilities of the ambient collectors.[56]

The MS harvester for AEH mentioned above only distributes the collected energy in each unit cell of the MS array without rectification. Indeed, the 5×1 linear array of the rectified SRR structure was proposed in 2013, and its maximum RF-DC efficiency was only 36% (with input power level of 24 dBm) at 900 MHz.[57] Next, a rectifying MS harvester with the three-layer sandwiched structure was demonstrated, wherein all ELC unit cells of periodic array are connected together to one rectifying circuit by a RF combining network (from 64-elements to one output port) operating in 2.45 GHz with the maximum rectifying efficiency of 67% at 10 dBm.[58] Another sandwich MS structure was designed by electric ring resonator with 40% RF-DC efficiency at 12 dBm.[59] The development of a similar rectifying MS collector with dual-polarization was achieved by optimizing the arrangement of single-polarized cells with the efficiency of 70% at 9 dBm.[60] Recently, an improved three-layer structure without RF combining network has been proposed at 2.45 GHz, and the achieved RF-DC efficiency was up to 66.9% at 5 mW/cm^2.[61]

TABLE II. Comparison of performances among different MS for AEH.

Ref.(year)	Frequency (GHz)	P/λ_0[a]	Maximum Harvesting Efficiency (%)	Key idea and features
40(2012)	5.8	0.18	76	SRR resonator, Electrical small
43(2015)	3	0.08	97	ELC resonator, Near unity efficiency
45(2015)	5.55	0.34	93	Complementary SRR resonator, High-efficiency
49(2017)	5.8	0.30	93.1	Modified SRR resonator Polarization independent & wide angle
50(2018)	5.8	0.32	88	Modified Electric Ring Resonator Simple structure Polarization independent & wide angle
51(2018)	2.5	0.13	90	Electrical small square closed-ring resonator Simple structure Polarization independent & wide angle
46(2015)	5.48	0.19	95	Complementary SRR resonator, wideband
47(2017)	6.2-21.4	0.44	96	Square ring resonator, wideband
48(2016)	1.75, 3.8, 5.4	0.18	90	Modified SRR resonator, Triple-band Polarization independent & wide angle
52(2017)	0.9, 2.6, 5.7	0.08	90	Multi-mode closed-ring resonator Tri-band, Miniaturized Polarization independent & wide angle
53(2016)	2.45	0.22	97	Split-loop resonator, 3D all-metal structure
54(2016)	2.47	0.18	97.2	Circular SRR resonator, Polarization selected
55(2018)	2.45, 6	0.09	95	Closed-ring resonator, Coded
56(2019)	5.33	0.13	86	Modified Complementary SRR resonator Flexible
57(2013)	0.9	0.12	36 at 24 dBm	SRR resonator, with rectification
58(2016)	2.45	0.12	67 at 10 dBm	ELC resonator, with rectification
59(2017)	3	0.15	40 at 12 dBm	Electric Ring Resonator, with rectification
60(2017)	2.4	0.14	70 at 9 dBm	Closed-ring resonator, with rectification Dual-polarization
61(2016)	2.45	0.16	66.9 at 5 mW/cm^2	ELC resonator, with rectification
62(2014)	2.18	0.21	28 at 0 dBm	I-shaped resonator, with rectification
63(2013)	1	0.12	25 at -6 dBm	FSS resonator, Dual-polarization with rectification and integrated design
64(2017)	6.75	0.67	50 at 0 dBm	Cut-wire resonator with rectification and integrated design

[a]P is the period of the MS unit cell, λ_0 is the free space wavelength at the operation frequency.

When integrating the rectifying function to MS harvester, it may introduce more losses and manufacturing errors due to additional impedance matching for multi-loads and large-scale RF or DC combining network, resulting in the complexity of the existing rectified MS structure and the decline of the harvesting efficiency. An effective solution is coplanar integrated design of MS and rectifying diode to enhance the overall performance of the MS harvester. The early concept of the coplanar optimal matched rectifying surface including the I-shaped MS embedded with the rectifying diode for the SPS was proposed in 2014, the RF-DC efficiency was only 28% at 0 dBm.[62] Then, the polarization-independent coplanar design of gridded-square-loop FSS with diodes was proposed for AEH, but as the size of the FSS array increases, the efficiency of RF-DC is almost reduced, while it also brings the challenge of impedance matching.[63] Very recently, a concept of a single-layer rectifying MS periodic array has been proposed for AEH.[64] The structure is composed of cut-wire MS integrated diode with better matching, and a thin highly inductive wire were adopted to connect all cells without the need of power combining network. It only has the simulation result of 50% rectifying efficiency at 0 dBm. Recent advances in rectennas have demonstrated that the antenna harvesting surfaces integrated diodes could achieve high-efficiency from medium to high power levels.[65-67] This provides a good idea for the integrated AEH harvester design of rectifier and MS.

Along the recent research and development (R&D), the MS harvesters for AEH have evolved from single-band to multi-band or wideband, from single-polarization to multi-polarization, or even polarization-insensitive and wide-angle reception, so that it could efficiently capture the energy from the ambient RF sources. The significant progress and evolution of the MS harvester for AEH were summarized in Fig. 2. Each generation of MS collector has a variety of structural designs to improve performance or add functions. But in essence, the MS collectors are mainly based on the strong electric/magnetic resonance or coupling of electrical small unit cells (equivalent to RLC resonators) to capture and convert electromagnetic energy. As a summary, the key parameters, ideas and features of various typical MS collectors are given in Table II. The future perspectives of MS in AEH applications are discussed below.

Compared with the conventional antenna, the MS array harvester could maximize the AEH efficiency per unit physical area of the MS. As outlined in this review, most of the existing MS collectors and commercial energy harvesting receivers using more than 0 dBm input power, the development of efficient energy harvesting technology remains a challenge for the weak power density scenarios in the real-world environments.[1,58-61] In addition to updating semiconductor tubes for low power,[6] it is expected that the R&D of the MS harvester for AEH could improve the performance in terms of the miniaturization, high-efficiency and self-adaptability (e.g. in operating frequency, polarization angle, impedance matching), hence to realize efficient energy harvesting under various environment on demand. And the development of MS harvester will also constantly benefit from the advances in MS such as design concept, structure manufacture and multiple applications.

MS has made exciting progress in many applications. Recent research advances indicate that MS is moving towards miniaturization, self-adapting, programable and digitalization[68-80]. The progress of intelligent MS has enhanced the ability of MS to manipulate EM waves to the higher level, which not only enrich the research field of MS, such as tracking and imaging[70,73,76,77], but also has important significance for other applications of MS. These trends also provide potential reference and development ideas for MS in AEH applications.

The latest development of rectenna and rectifier circuit have found significant impact in MS harvester, which could provide a good idea for the adaptive dynamic range of impedance, frequency, and input power.[18-25] Other unique features, such as flexible materials,[81] reconfigurable or tunable designs,[82] and quantum driving algorithm,[83] may also enhance the performance of the MS harvester.

The MS would be combined with antennas and even different types of harvesters to achieve multifunction simultaneously, therefore, which significantly enhances the performance of MS collector and could also benefit other energy applications., such as multi-service antenna,[84] hybrid RF and solar harvester and so on.[85] This may also bring tremendous opportunities for the multi-field development of MS and practical energy applications.

In summary, metasurfaces can not only enable efficient ambient RF energy harvesting, but also extend the potential function for various kinds of AEH devices. It is a great approach to deal with some key issues of WPT and AEH including efficiency, distance, size and impedance matching. In the near future, we expect that MS can form commercial standards in AEH applications such as sensor network power supply just like the current standardization and regulation of the WPT[1,4], which will be of great significance. We hope that the metasurfaces for ambient energy harvesting will bring us all a bright future.

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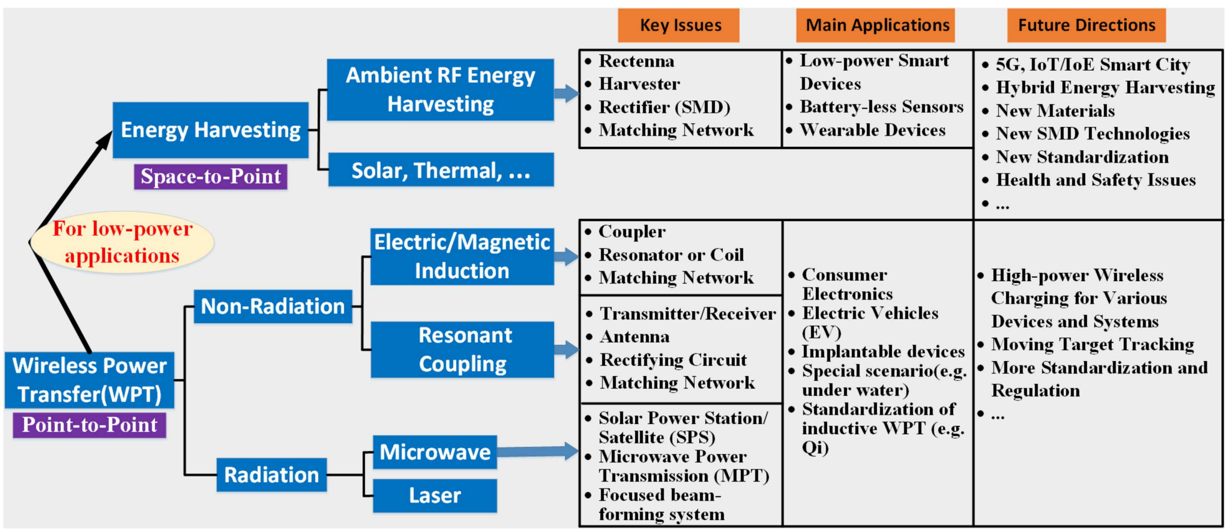
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Future Directions
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Energy Harvesting
Space-to-Point
Solar, Thermal, ...
• Rectenna
• Harvester
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• Battery-less Sensors
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• ...
For low-power applications
Electric/Magnetic Induction
Non-Radiation
Resonant Coupling
Wireless Power Transfer(WPT)
Point-to-Point
Radiation
Microwave
Laser
• Coupler
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• Matching Network
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• Solar Power Station/ Satellite (SPS)
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• High-power Wireless Charging for Various Devices and Systems
• Moving Target Tracking
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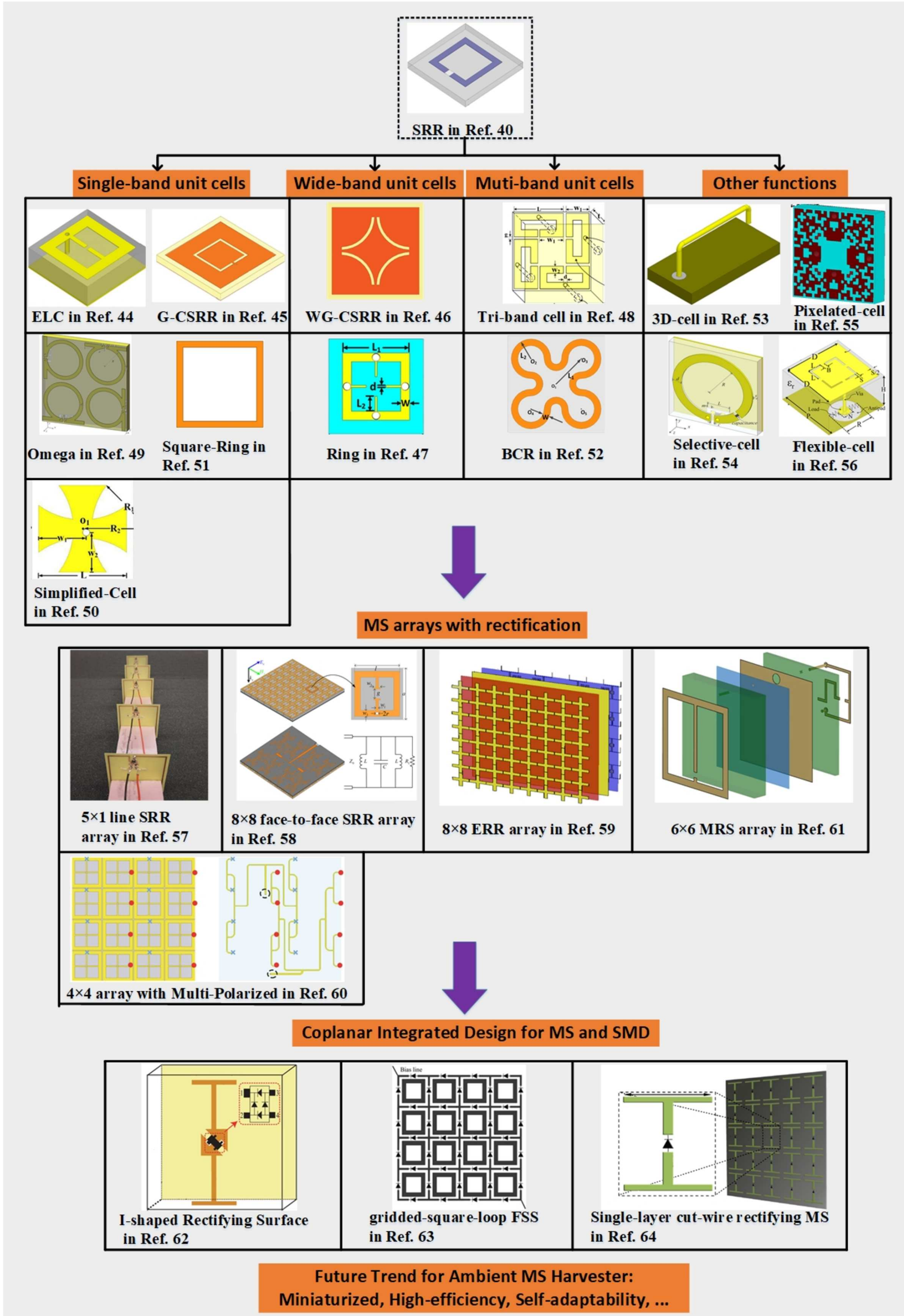
• ...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